Rotating Targets

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Some uses of the technology

- Developed for tensor polarization enhancement

  - Proposed and possible projects

  - Status of the technique and further
- Applications for Raster with HIPS

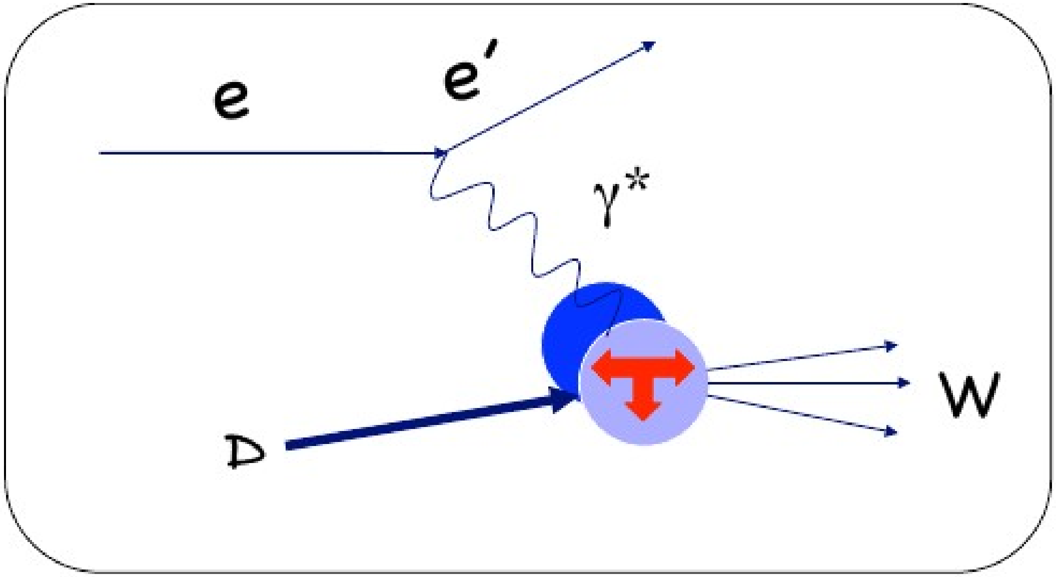
  - Why its needed

  - Proof of concept
- Combination of technologies and where to take it

Exploring Tensor Polarization

- Hidden Color (non-nucleonic) degrees of freedom
- Tensor polarization of the Sea Quarks
- Study the signature of exotic effects in nuclei
- Probing quark behavior while depending on nucleon spin state
- Investigate nuclear effects at the parton level

Inclusive Scattering



Construct the most general Tensor W consistent with Lorentz and gauge invariance

Frankfurt & Strikman (1983)

Hoodbhoy, Jaffe, Manohar (1989)

$$
\begin{aligned}
W_{\mu\nu} \quad = \quad & -F_1 g_{\mu\nu} + F_2 \frac{P_\mu P\nu}{\nu} \\
& + i\frac{g_1}{\nu}\epsilon_{\mu\nu\lambda\sigma} q^\lambda s^\sigma + i\frac{g_2}{\nu^2}\epsilon_{\mu\nu\lambda\sigma} q^\lambda (p\cdot q s^\sigma - s\cdot q p^\sigma) \\
& \left.\begin{aligned} & -b_1 r_{\mu\nu} + \frac{1}{6} b_2 (s_{\mu\nu} + t_{\mu\nu} + u_{\mu\nu}) \\ & + \frac{1}{2} b_3 (s_{\mu\nu} - u_{\mu\nu}) + \frac{1}{2} b_4 (s_{\mu\nu} - t_{\mu\nu}) \end{aligned}\right\} \text{Tensor Polarization}
\end{aligned}
$$

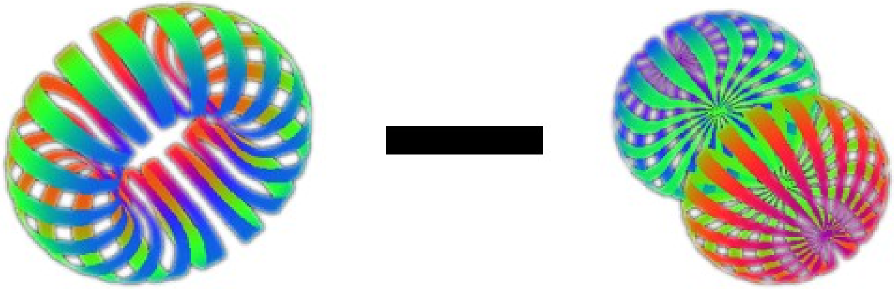
Inclusive Scattering

$$\left.\begin{aligned}&-b_1 r_{\mu\nu} + \frac{1}{6} b_2 (s_{\mu\nu} + t_{\mu\nu} + u_{\mu\nu})\\ &+\frac{1}{2} b_3 (s_{\mu\nu} - u_{\mu\nu}) + \frac{1}{2} b_4 (s_{\mu\nu} - t_{\mu\nu})\end{aligned}\right\} \text{Tensor Polarization}$$

$$b_1(x) = \frac{q^0(x) - q^1(x)}{2}$$

q^0 : Probability to scatter from a quark (any flavor) carrying momentum fraction x while the *Deuteron* is in state m=0

q^1 : Probability to scatter from a quark (any flavor) carrying momentum fraction x while the *Deuteron* is in state |m| = 1

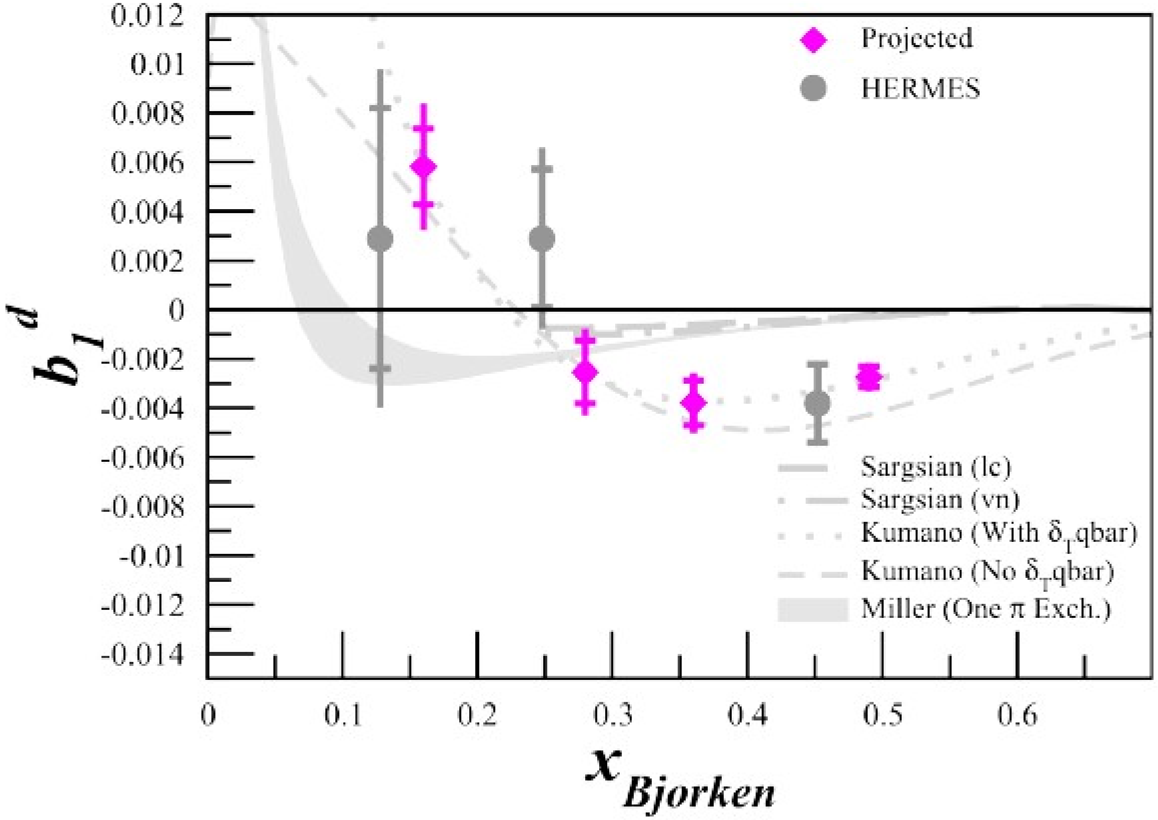


b_2 : related to b_1 by A Callan-Gross relation

b_4 : Also Leading Twist, but kinematically suppressed for a longitudinally polarized target.

b_3 : higher twist, like g_2

The Measurement



$$A_{zz} = \frac{2}{fP_{zz}} \frac{\sigma_{\dagger} - \sigma_0}{\sigma_0}$$

$$= \frac{2}{fP_{zz}} \left(\frac{N_{\dagger}}{N_0} - 1 \right)$$

$$b_1 = -\frac{3}{2} F_1^d A_{zz}$$

$\sigma_{\dagger}$: Tensor Polarized cross-section

σ_0 : Unpolarized cross-section

I) Systematics

TAC : Important to control measured false asymmetries to better than 6 x 10^{-4}.

TAC : *"We believe this is possible with a combination of upgrades to Hall C infrastructure and sufficient commitment by the collaboration to control the unusual systematic issues of this experiment."*

Systematics

Impact on the observable

$$\delta A_{zz} = \pm \frac{2}{f P_{zz}\sqrt{N_{cycles}}}\delta\xi$$

Dedicated team to systematics/false asyms

similar manpower requirement to g2p exp. where we had several teams completely separate from the polarized target effort.

$\delta\xi$

Charge Determination

< 2 x 10^{-4}, mitigated by thermal isolation of BCMs and addition of 1 kW Faraday cup

Luminosity

< 1 x 10^{-4}, monitored by Hall C lumi

Target dilution and length   step like changes observable in polarimetry

< 1 x 10^{-4}

Beam Position Drift effect on Acceptance

< 1 x 10^{-4} (we can control the beam to 0.1 mm, raster over 2cm diameter)

Effect of using polarized beam

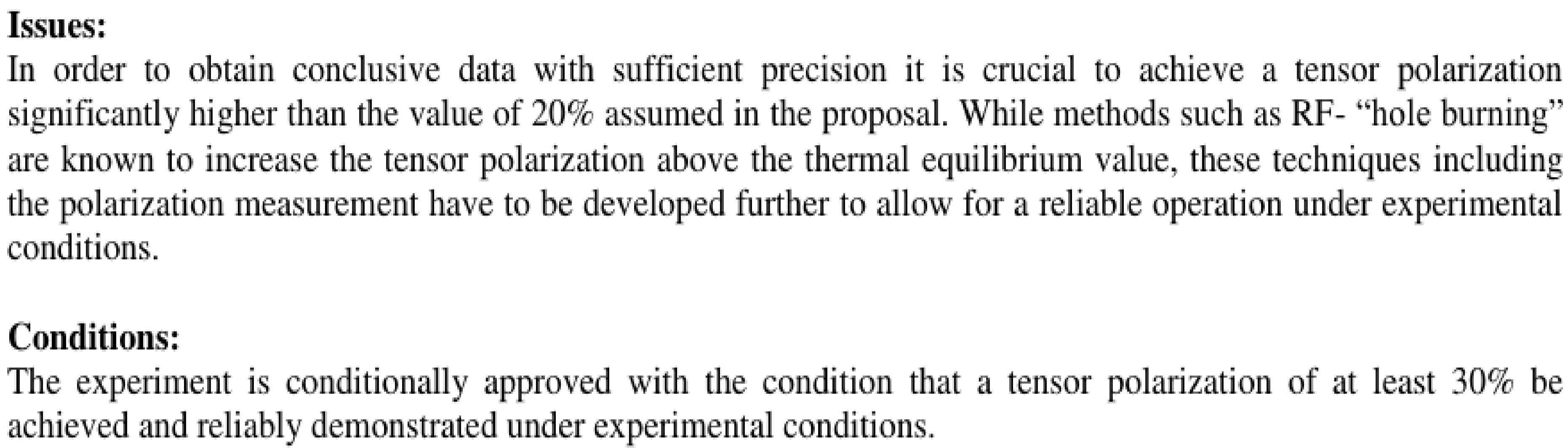
< 2.2 x 10^{-5}, using parity feedback

PAC Conditions

Scientific Rating: A-

Recommendation: Conditional Approval (C1)

- E12-13-011 (*The Deuteron Tensor Structure Function b1*)
- E12-15-005 (*Tensor Asymmetry in Quasielastic Region*)



Issues:

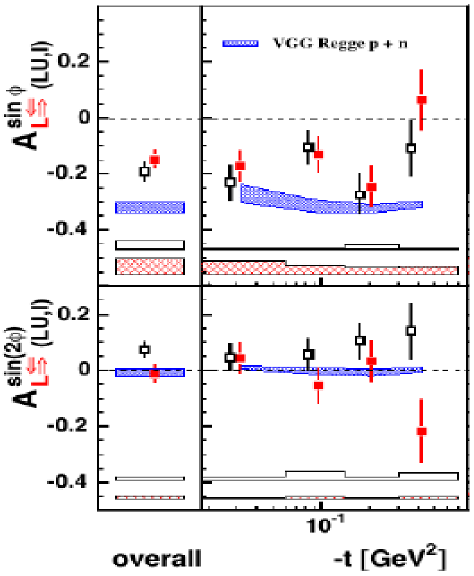
In order to obtain conclusive data with sufficient precision it is crucial to achieve a tensor polarization significantly higher than the value of 20% assumed in the proposal. While methods such as RF- “hole burning” are known to increase the tensor polarization above the thermal equilibrium value, these techniques including the polarization measurement have to be developed further to allow for a reliable operation under experimental conditions.

Conditions:

The experiment is conditionally approved with the condition that a tensor polarization of at least 30% be achieved and reliably demonstrated under experimental conditions.

Other Possible Projects

- Spin-1 SIDIS, Spin-1 DVCS, Spin-1 TCS(HIPS), GDH(HIPS), Deuteron T20(HIPS), T21(HIPS), T20(HIPS), Unnatural Parity exchange (HIPS), Polarized gluons in the nucleon(HIPS), tensor polarized meson photoproduction C_{BT}^{21}, C_{BT}^{20}



☐ **unpolarized**
$\mathcal{Re}(\mathcal{H}_1)$

🟥 **tensor-polarized**
$\mathcal{Re}(\mathcal{H}_1 - ⅓\mathcal{H}_5)$

DVCS A_{LZZ} (tensor asymmetry) sinϕ amplitude:
(no plot shown)
0.074 ± 0.196 ± 0.022

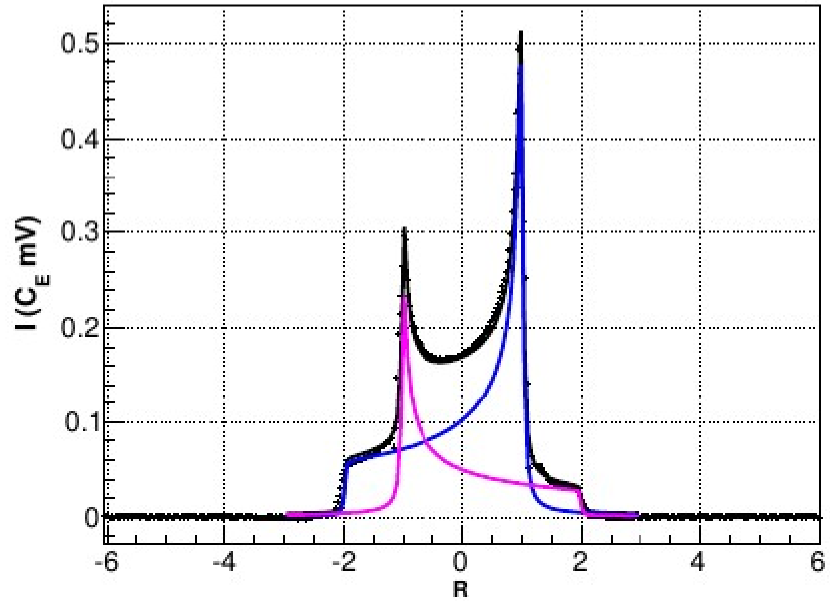
$$\begin{aligned}\frac{d\sigma}{d\Omega} &= \frac{d\sigma_0}{d\Omega}\{1-\sqrt{3/4}P_z\sin\theta_{d\gamma}\sin\phi T_{11}\left(\theta_p^{cm}\right)\\ &+ \sqrt{1/2}P_{zz}[(3/2\cos^2\theta_{d\gamma}-1/2)T_{20}\left(\theta_p^{cm}\right)\\ &- (\sqrt{3/8}\sin 2\theta_{d\gamma}\cos\phi T_{21}\left(\theta_p^{cm}\right)\\ &+ (\sqrt{3/8}\sin^2\theta_{d\gamma}\cos 2\phi T_{22}\left(\theta_p^{cm}\right)]\},\end{aligned}$$

Options of Enhancement

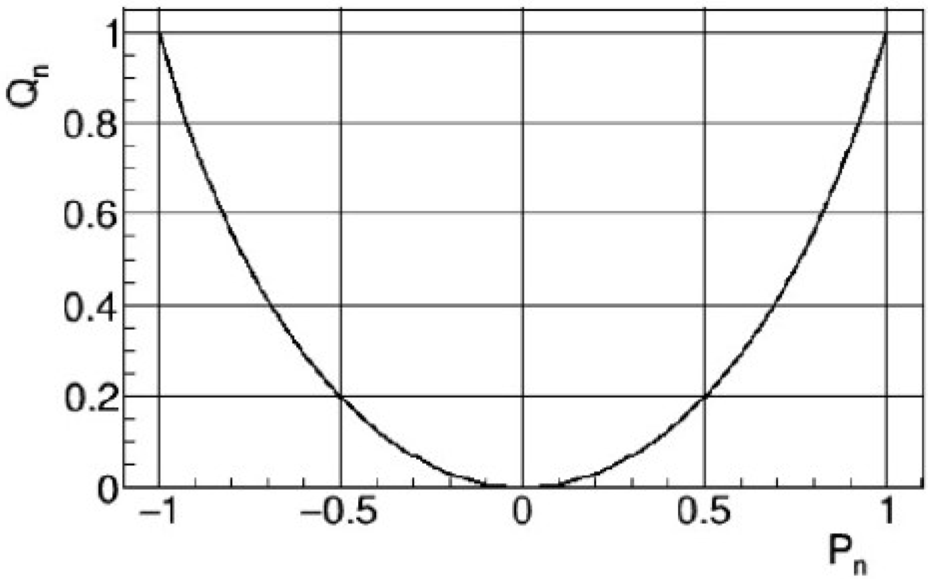
- Increase the B-Field
- Manipulate using AFP
- Additional Microwave Sources
- Different Materials
- RF Saturation (hole burning)

Selective Semi-saturation

(or just hole burning)



$$R = \frac{\omega - \omega_d}{3\omega_q}$$



$$P_n = \frac{2\hbar}{g^2\mu_N^2 \pi N}\int_{-\infty}^{\infty} \frac{3\omega_Q\omega_D}{3R\omega_Q + \omega_D}\chi''(R)dR$$

$$= \frac{1}{C_E}\int_{-\infty}^{\infty} I_+(R) + I_-(R)dR,$$

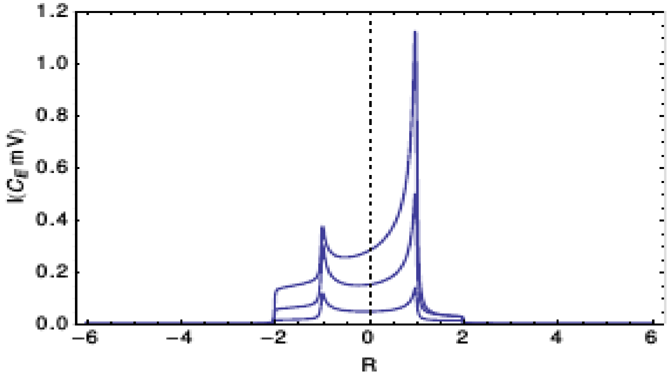
$$Q_n = (I_+ - I_-)/C_E$$

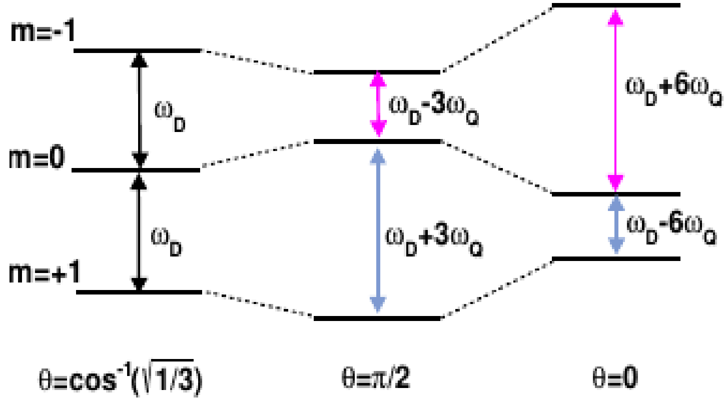
$$Q_n = 2 - \sqrt{4 - 3P_n^2}$$

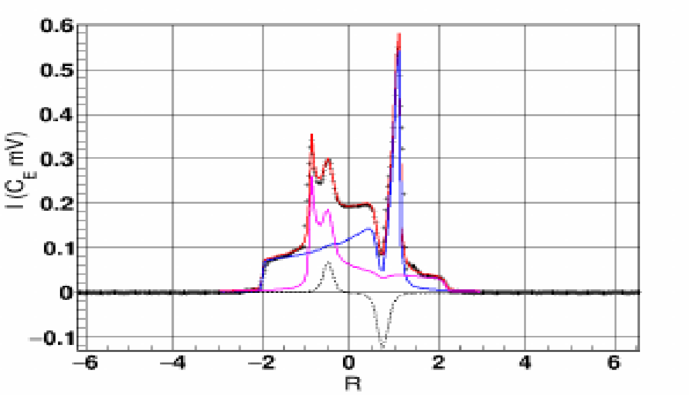
- Under Boltzmann equilibrium the relationship between vector and tensor polarization always exists
- Under this same condition the Height of each peak maintains a relationship to each other that contains all polarization information
- The ratio of the peak intensities can be used to calculate relative population in each magnetic sub-level

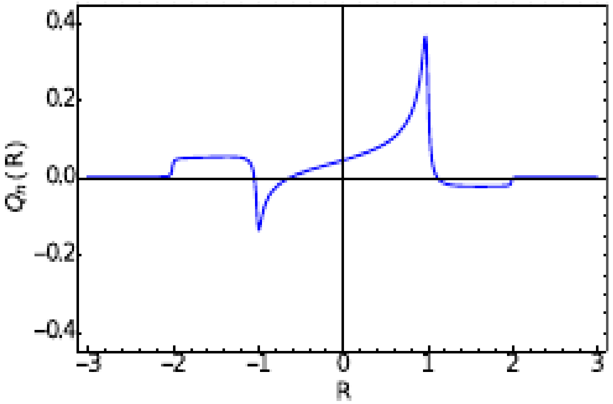
Selective Semi-saturation

(or just hole burning)





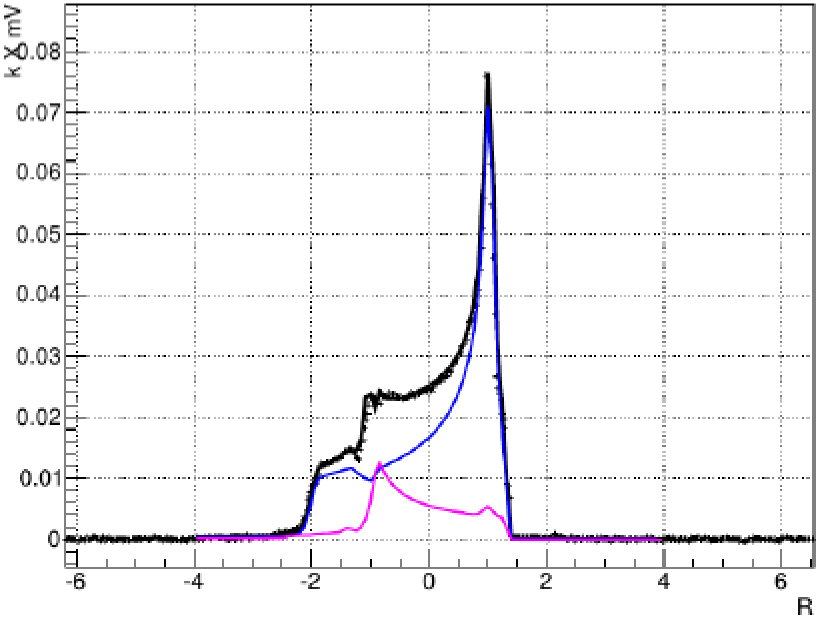




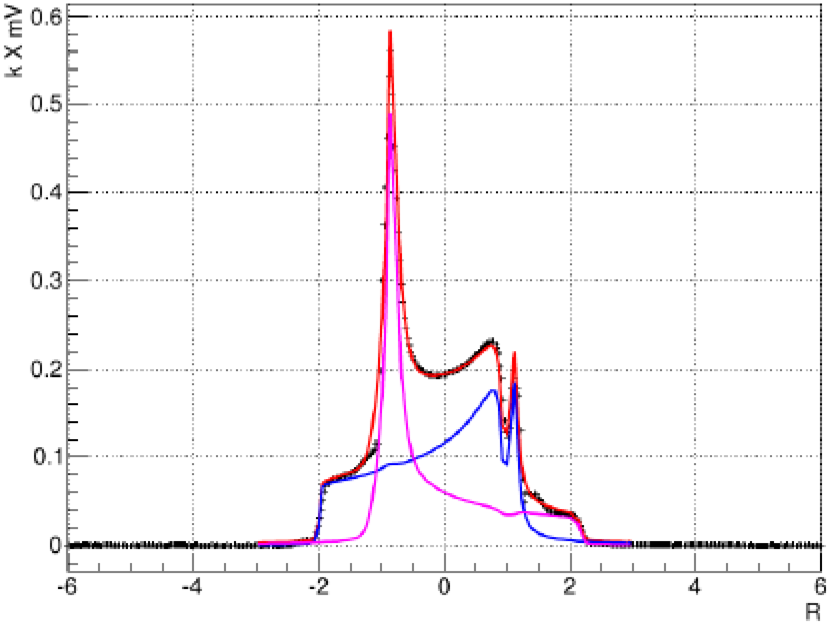
- RF manipulation of the CW-NMR line
- Enhanced by negating the values below zero
- Can be implemented during DNP

Selective Semi-saturation

(or just hole burning)



MC overlap with d-but. NMR experimental points (Pn=51→45,Qn:20→31%)

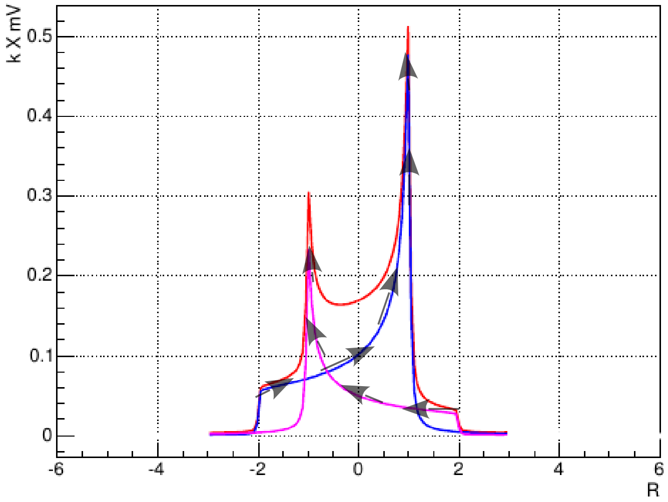


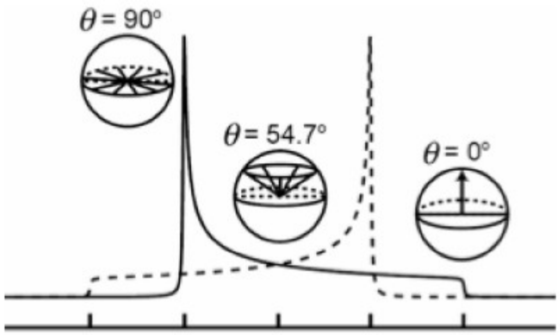
MC with fit and d-but. NMR experimental points (Pn=48→46,Qn:18→6%)

$$R = \frac{\omega - \omega_d}{3\omega_q}$$

DK Eur.Phys.J. A53 (2017) no.7, 155 arXiv:1707.07065

Rotating Target Concept





- Selective saturation/pumping while rotating
- Saturated domain moves with rotation
- Can enhance Q or go -Q

RF-Manipulated Signals

Fast target helicity flips through Adiabatic Fast Passage (AFP)

AFP at UVA

performed AFP on different materials (5T, 1K)

15NH3, D-butanol, butanol+tempo

preliminary results on flip efficiency

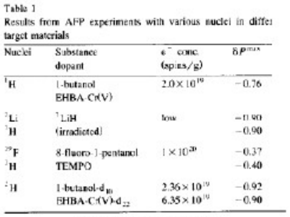
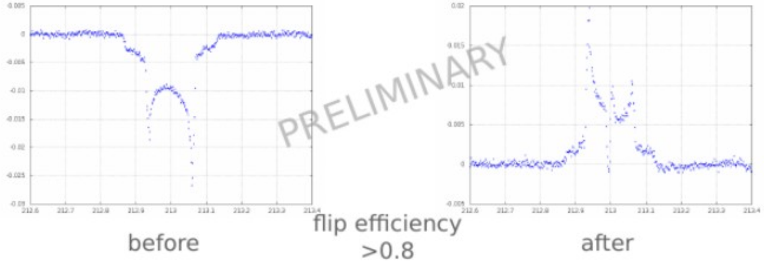


Table 1
Results from AFP experiments with various nuclei in differ
target materials

Nuclei	Substance dopant	e^- conc. (spins/g)	δP^{max}
^{1}H	1-butanol EHBA-Cr(V)	2.0×10^{19}	−0.76
^{7}Li ^{1}H	^{7}LiH (irradiated)	low	−0.90 −0.90
^{19}F ^{1}H	8-fluoro-1-pentanol TEMPO	1×10^{20}	−0.37 −0.40
^{2}H	1-butanol-d$_{10}$ EHBA-Cr(V)-d$_{22}$	2.36×10^{19} 6.35×10^{19}	−0.92 −0.90

NIM 356 (1995) 108

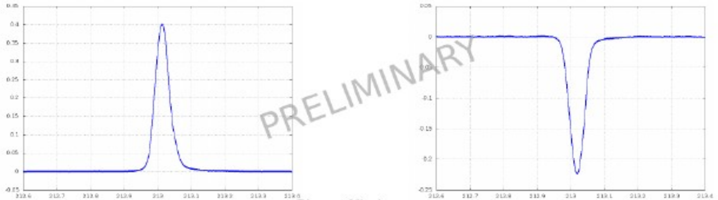


before

flip efficiency
>0.8

after

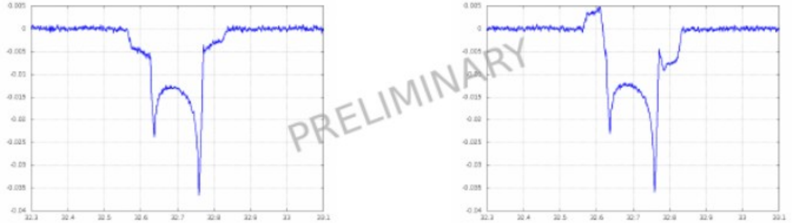
15NH3



before

flip efficiency
0.55

after

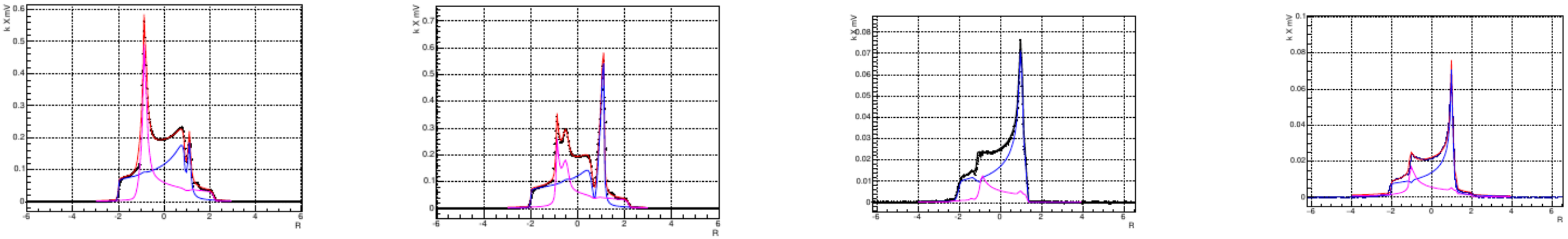


before

after

AFP produces rotation of the macroscopic magnetization vector by sweeping through resonance in a short time compared to the relaxation time

- Set record for Tensor Polarization for Deuteron (d-b only) Q>31% @1K 5T
- Set record for AFP flip with Proton e>50% @ 1K 5T



Achieved so far

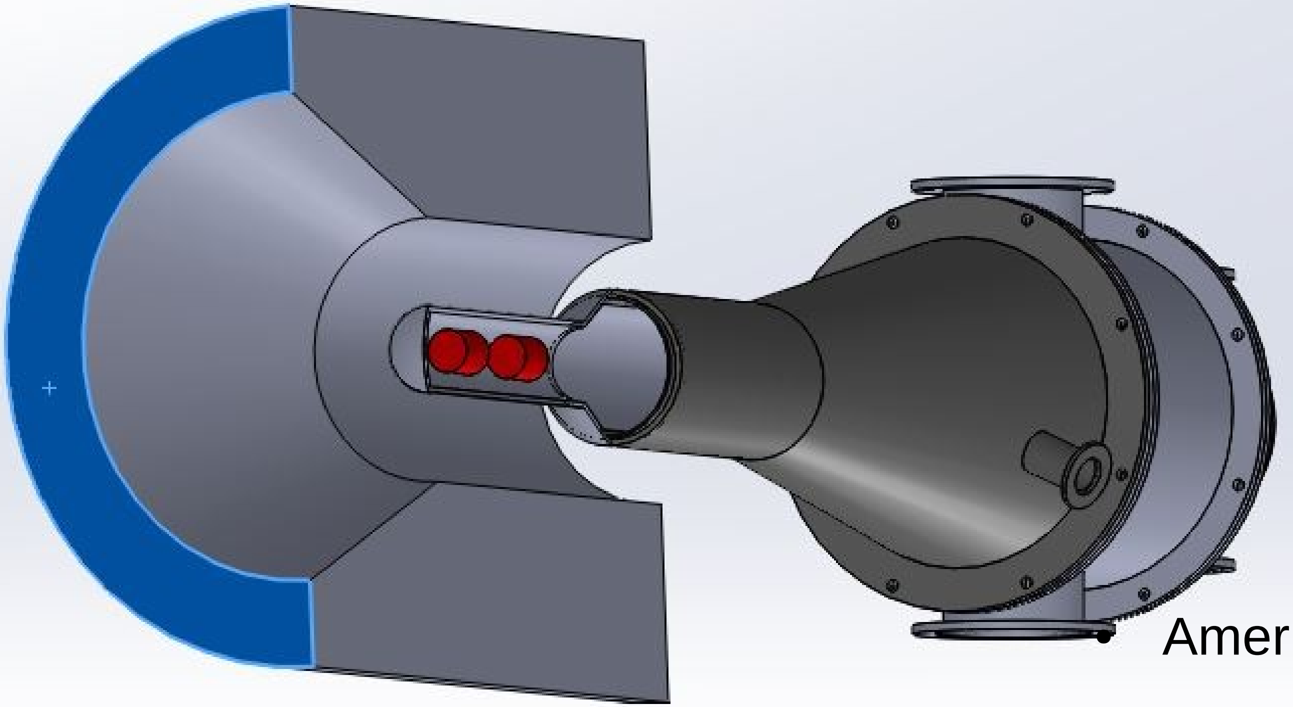
- Before recent research (1984): ~20%
- Recent studies SSS (2014-2015): ~30%
- AFP with SSS (2016): ~34%
- Rotation SSS so far: ~38% (neg Q possible)

Still more to come, we can probably do much better than this by improving B/T should expect Q>>40%

How to do better

- Solenoid with stronger field for longitudinal
- Lower temperatures with optimized cooling
- Two simultaneous helicity states

Solenoid with Horizontal Fridge



- American Magnetics

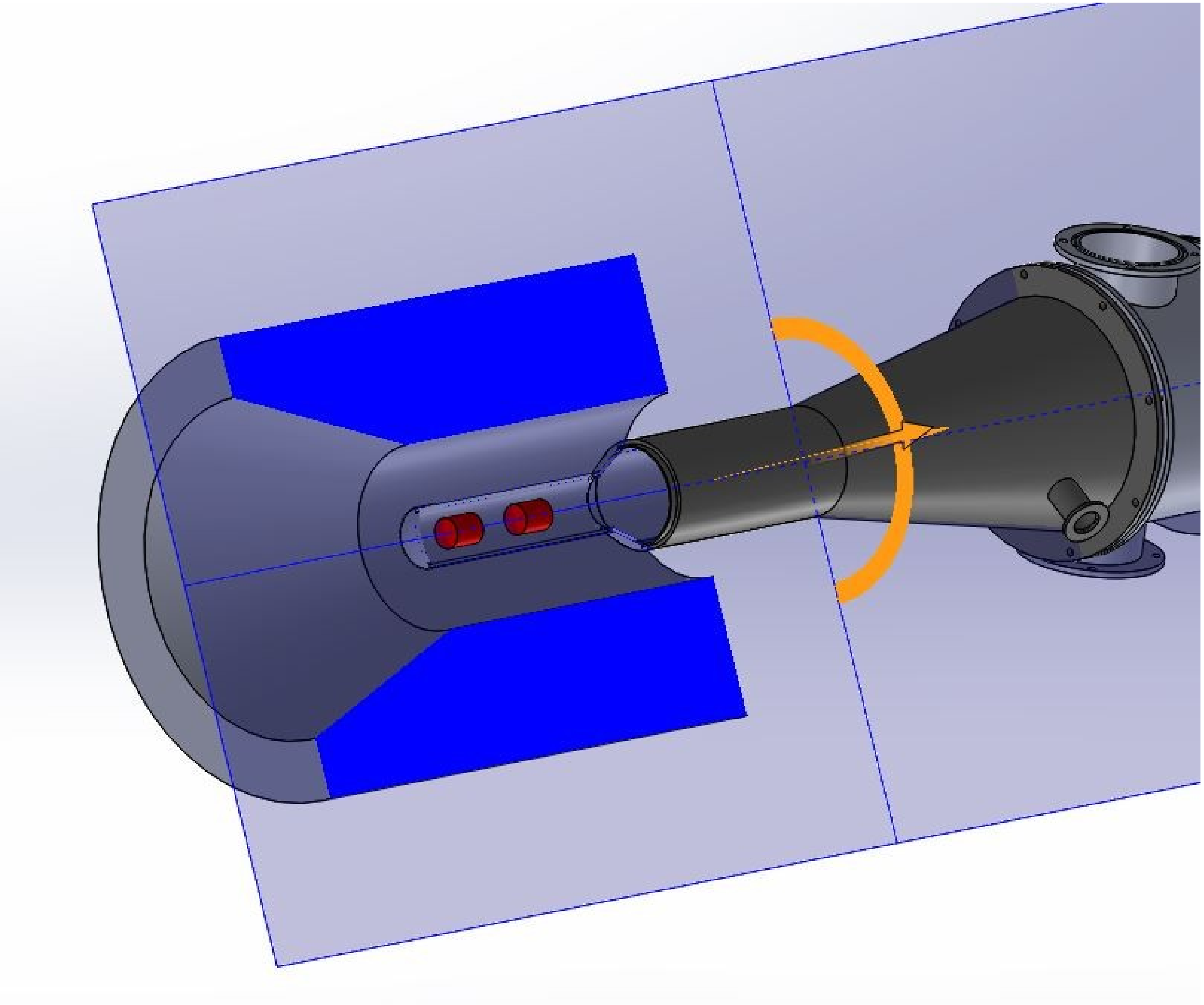
- 12” bore

- 10^-4 homogeneity

- 6” homogeneous region

- bell housing dewar

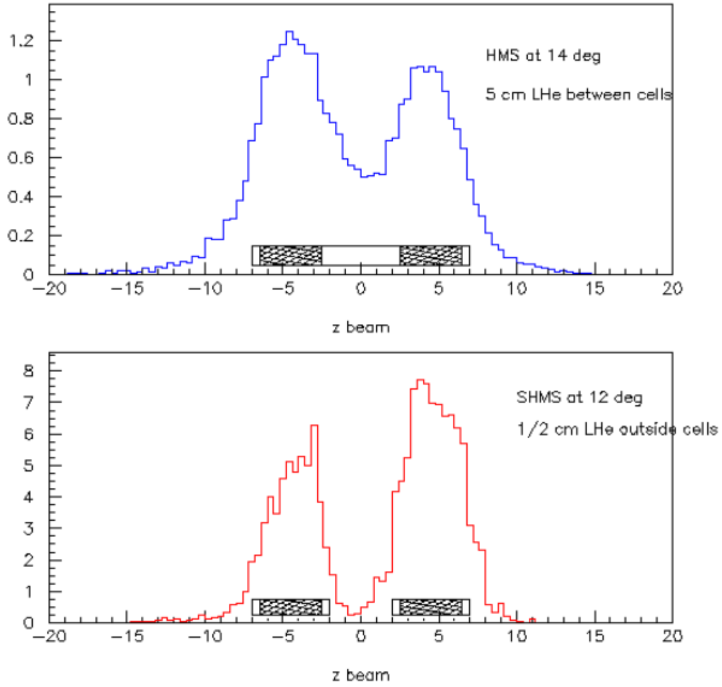
Hall C?



- Single Microwave
- Separate holding coils
- Could be use with HIPS and HI-e

Two cell Separation

- Vertex reconstruction allows identifying data from individual cells
- Clean separation with small loss of events from ends of cells



- Example: simulated HMS[1]
  - 4 + 4 cm upstream + downstream cells

    5 cm LHe between cells

    0.5 cm at ends
- Example: simulated SHMS[1]
  - 0.5 cm LHe outside cells (at all ends)

[1] http://iopscience.iop.org/article/10.1088/1742-6596/543/1/012013/pdf

Cooling Power

$$\boxed{P \propto \exp(-\frac{L}{RT})}$$

Latent heat ^{4}He ~90 J/mol
Latent heat ^{3}He ~40 J/mol

Cooling power: exponentially small at low temperature
Pumping on ^{4}He T~1 K (normally down to 1.8 K)
Pumping on ^{3}He T~0.26 K (down to 0.3 K)

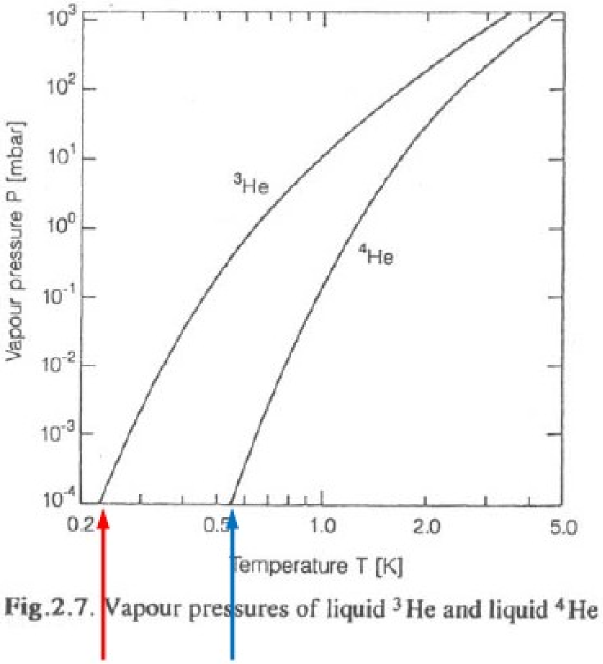
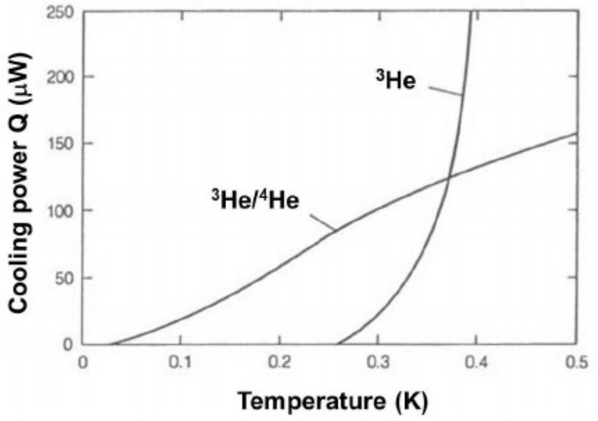


Fig.2.7. Vapour pressures of liquid ^{3}He and liquid ^{4}He

^{3}He-^{4}He dilution refrigeration: use the difference of the specific heats of the two phases (the enthalpy of mixing);

$$\Delta H \propto \int \Delta C dT \Rightarrow Q \propto x \Delta H \propto T^2$$

Dilution refrigerator
cooling power:~T^2

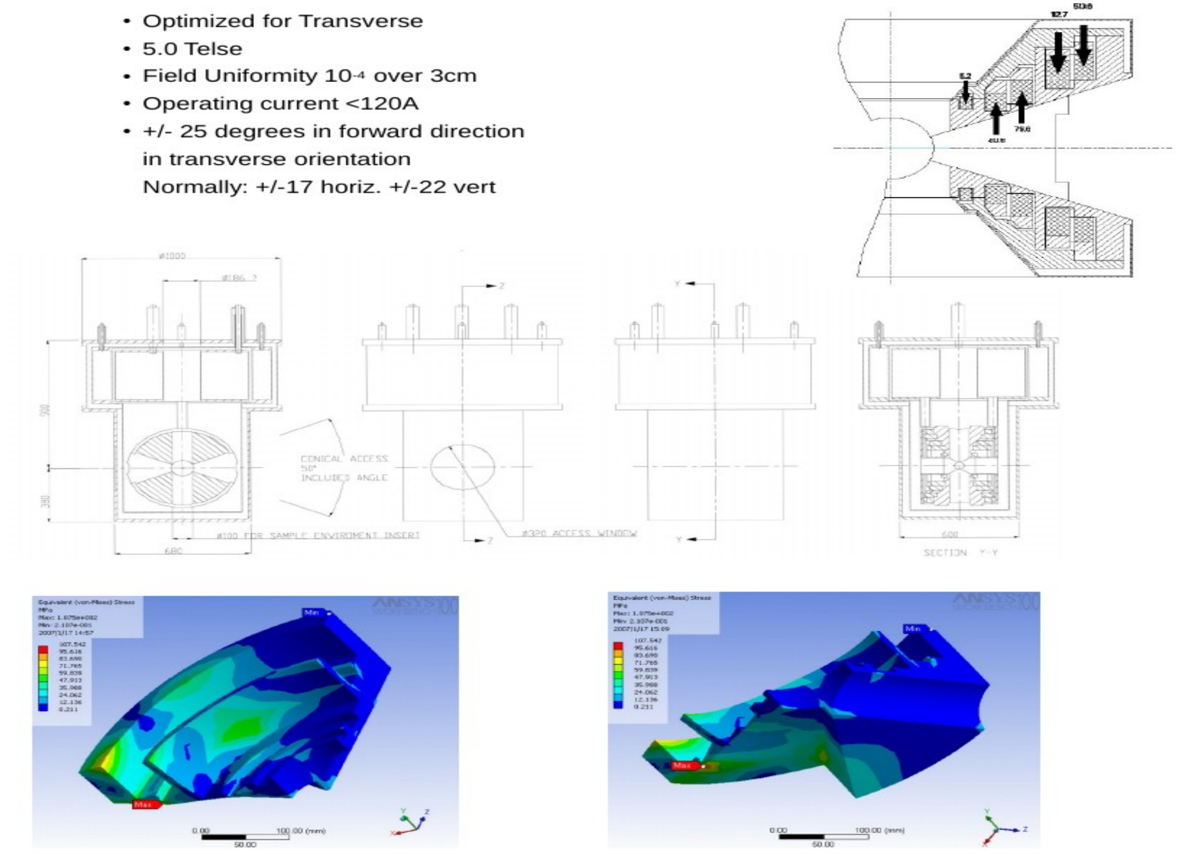


Supercooled ^{4}He Fridge

- Supercool with ^{3}He pumping
- Or with dilution ^{3}He-^{4}He mixing

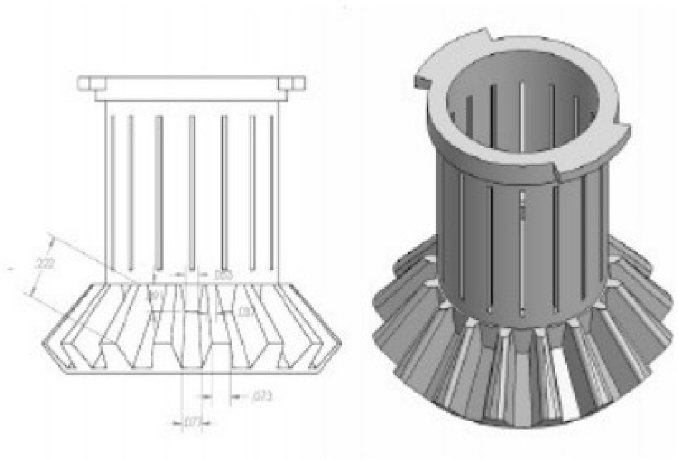
Other Magnets

- Drell-Yan 5T vertically pointing (only 10 deg)
- Also in conversation with Oxford about a cryogen free S vs N

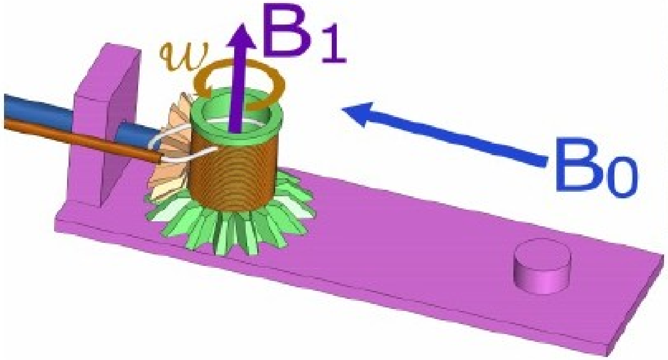


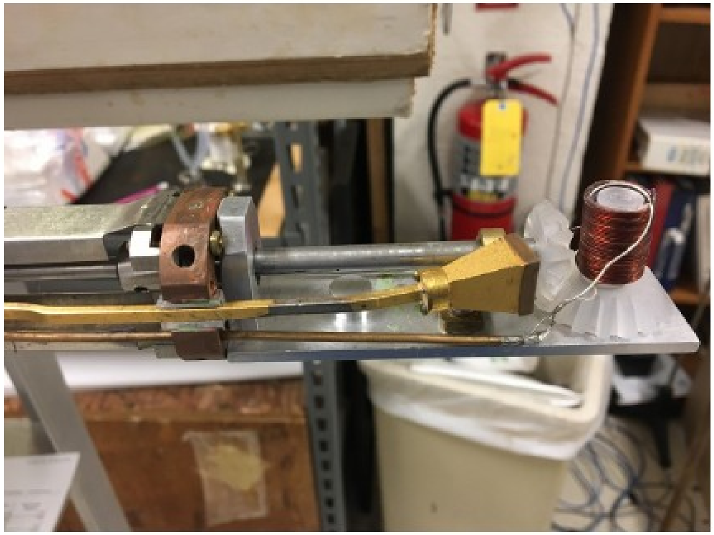
- Optimized for Transverse
- 5.0 Telse
- Field Uniformity 10-4 over 3cm
- Operating current <120A
- +/- 25 degrees in forward direction in transverse orientation
  Normally: +/-17 horiz. +/-22 vert

Raster Over Faces of Target



- Kel-F $(C_2ClF_3)_n$ cup and driving gear
- Motor outside cryostat
- NMR coil around cup
- Already used with several designs at UVA
- 1 Hz achieved with no problem
- Fixed beam spot





Why are we doing this

- Depolarization due to radiation damage

  - Photons at the several GeV scale can easily brake up NH_3

  - Especially with high energy (IPs) we get significant production of NH_2, Atomic H, Atomic N, and recombination to hydrazine and others

  - This radiation damage causes either different polarization mechanisms and/or depleted DNP

  - The production of these free radicals is the leading cause of target maintenance and overhead time required to anneal and replace target material

  - EGS and Geant indicate we will get some of these processes with a high energy photon but the primary production of centers is still NH_2, Atomic H from the IPs created by the photon source

  - Secondary scattering of ionizing radiation inside the target using 10^{11} gamma/sec with RMS~1 mm leads to 20 nA of e+/e- in an area of 4.5 mm^2

  - If this dose can be spread out over the surface of the target (570 mm^2) we start to approach the radiation damage seen in CLAS6 type running

- Depolarization due to localized beam heating

  - Local hot-spots caused by interfacial thermal heating can create loss of polarization at the beam location in the target

  - Additional heating issue arise from thermal conductivity of the material and the Kapitza resistance

  - All of this is easily handled by keeping the beam to target position moving (fix only a couple of seconds)

Its Worth Mentioning

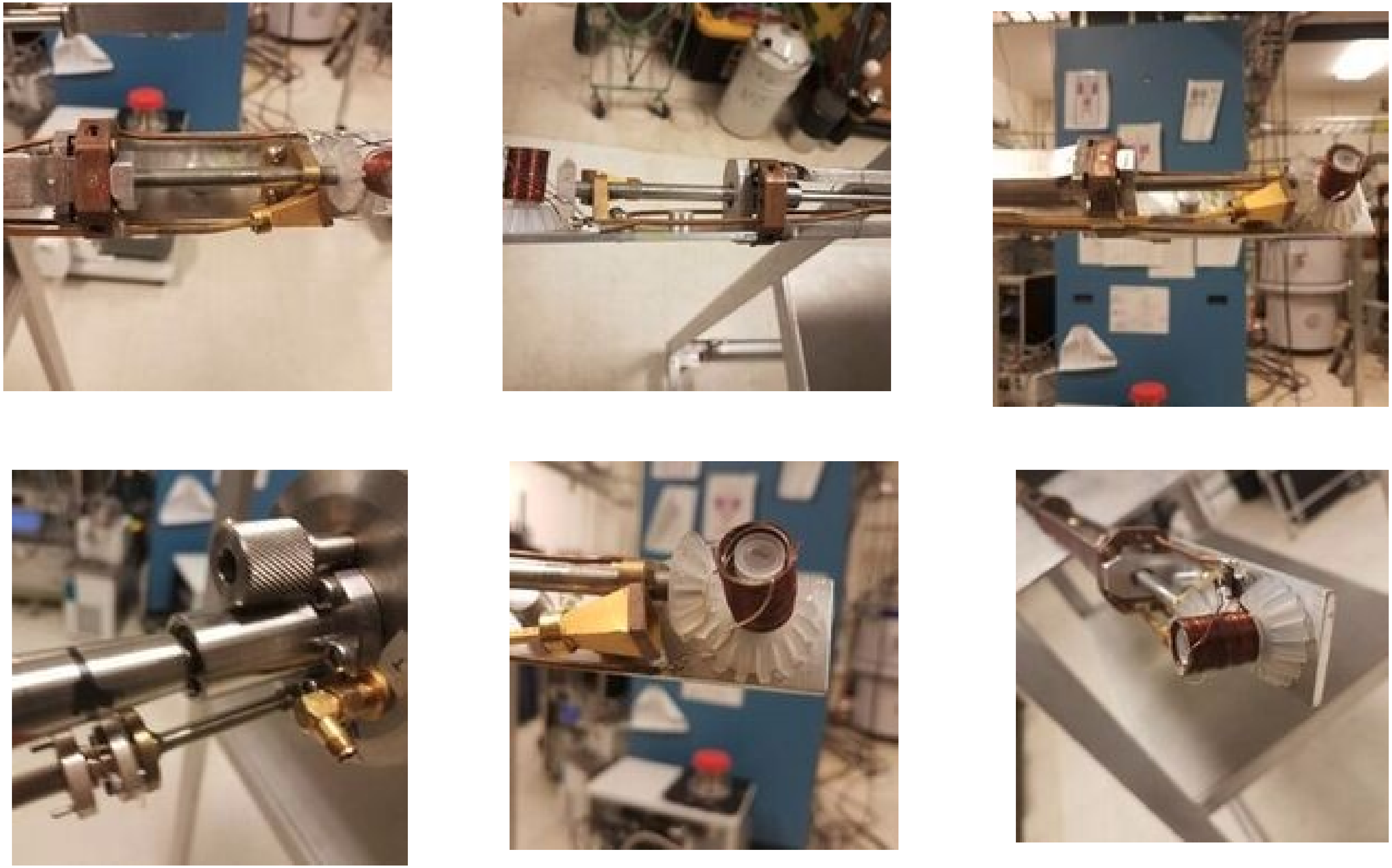
- Even with e-beam we know what some of the radiation damage processes are but not all of them
- The manifestation of these processes into 'bad' paramagnetic centers is beam energy and target temperature dependent with rate effects involved as well
- The photon beam production of paramagnetic centers may not be directly proportional to heat load as the 'bad' centers are less likely to be produced in the front of the target and almost only comes from pair production and e-Compton scattering at lower energy further in the target
- We should expect many more lower energy processes to terminate in the target that are not producing as many 'bad' centers as seen in electron beams
- But still mostly an open question when trying to consider numbers, a more sophisticated MC-effort maybe worthwhile to understand the profile of radiation damage in needed dimensions of this type of target (at least down the road)

What is New

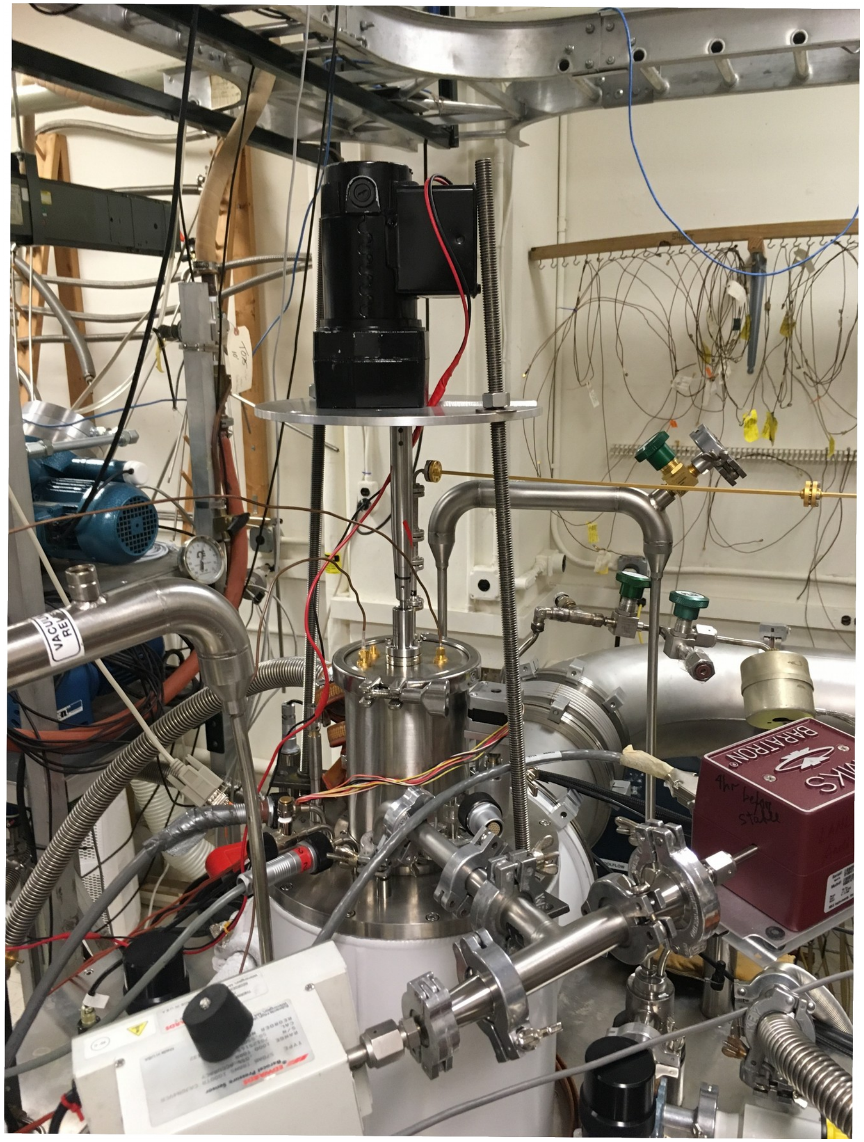
- Mechanical Rotary Vacuum Feed Through
- Geared Cups, size of cup can change but not necessary
- Use combination of already used target position actuator and rotation
- Connected Motor at the top of cryostat
- NMR coil must be on outside of cup (but this is actually not new)

Rotating System Currently Used

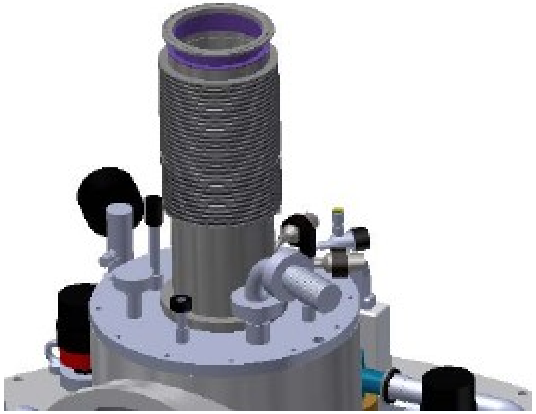
System Currently Used



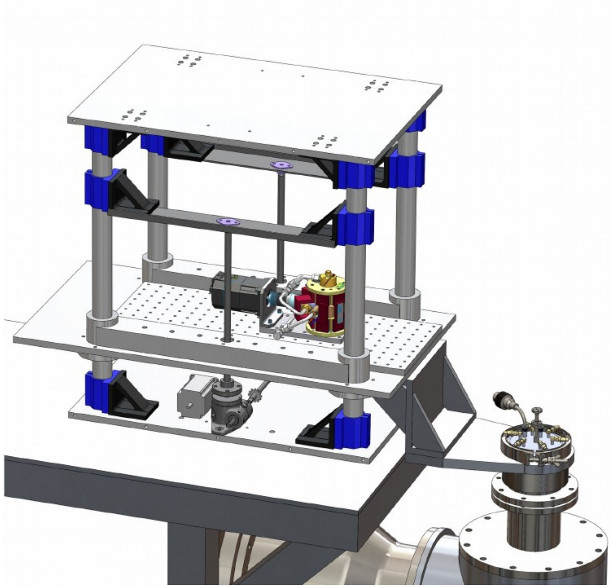
Rotating System Currently Used



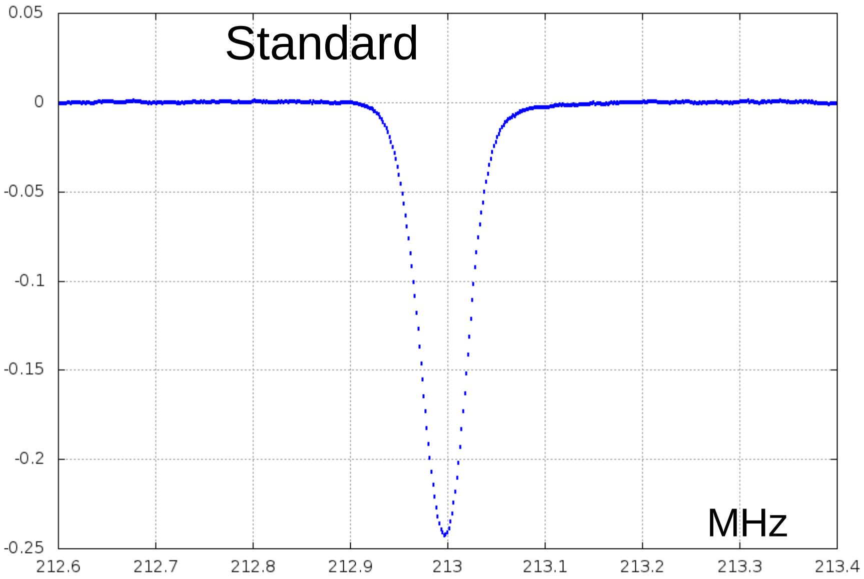
Motor Driven Circular Motion

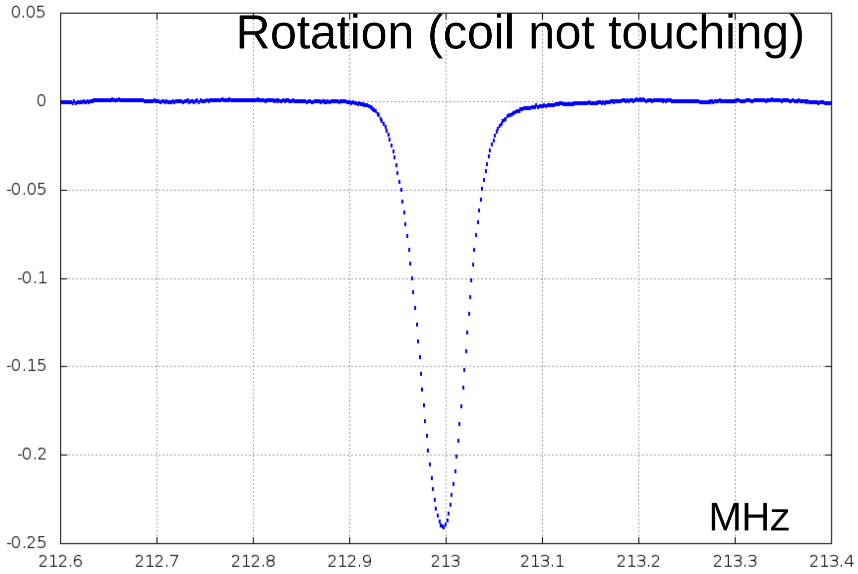


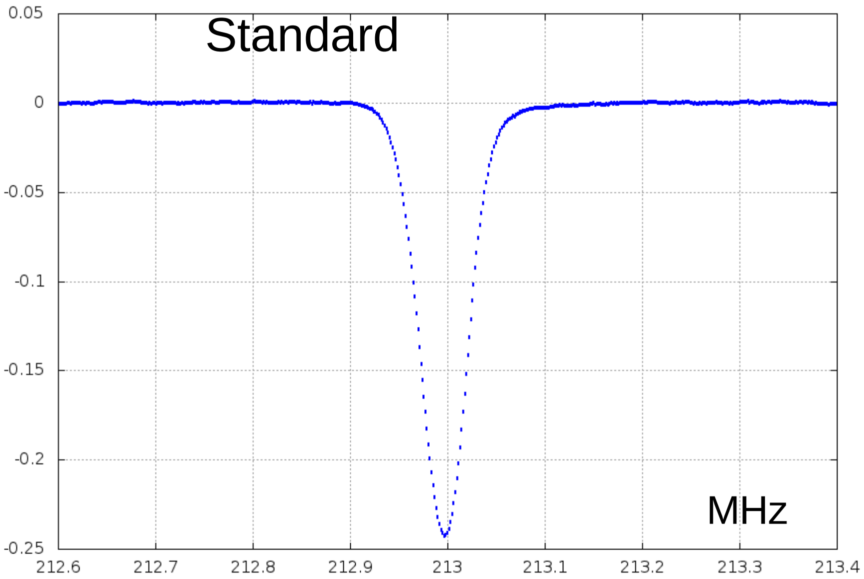
Actuator with Bellows for up and down

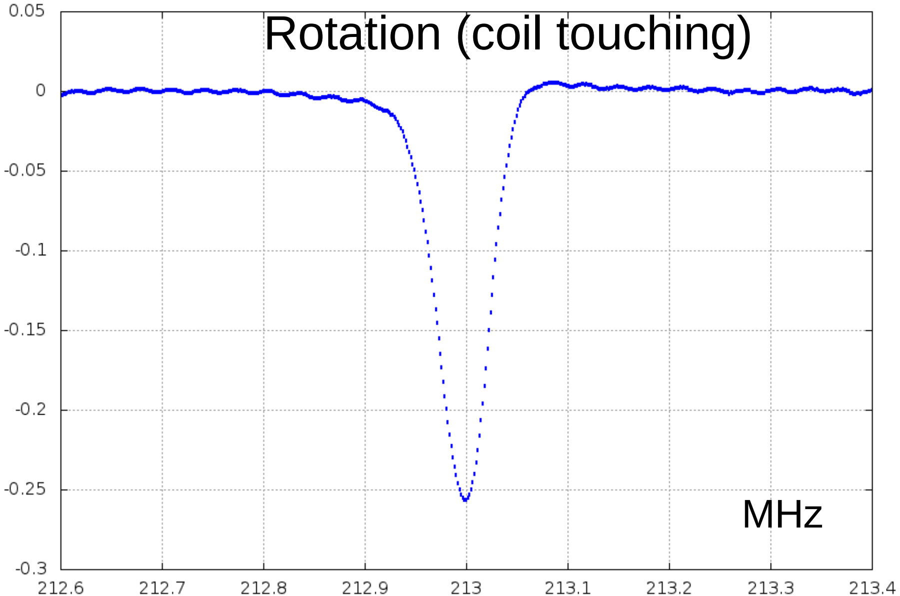


NMR-Tests


Standard
0.05
0
-0.05
-0.1
-0.15
-0.2
-0.25
212.6
212.7
212.8
212.9
213
213.1
213.2
213.3
213.4
MHz

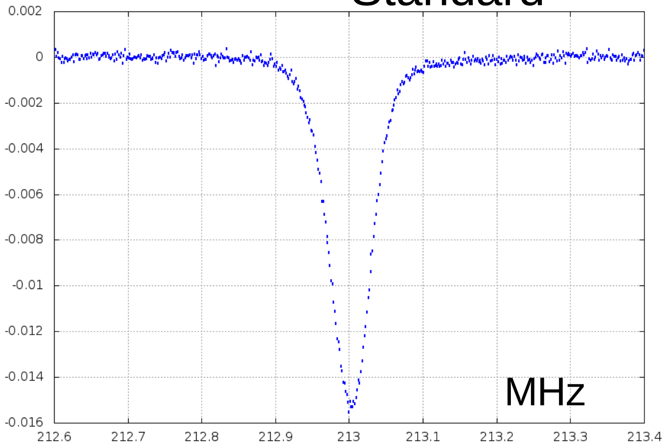

Rotation (coil not touching)
0.05
0
-0.05
-0.1
-0.15
-0.2
-0.25
212.6
212.7
212.8
212.9
213
213.1
213.2
213.3
213.4
MHz


Standard
0.05
0
-0.05
-0.1
-0.15
-0.2
-0.25
212.6
212.7
212.8
212.9
213
213.1
213.2
213.3
213.4
MHz

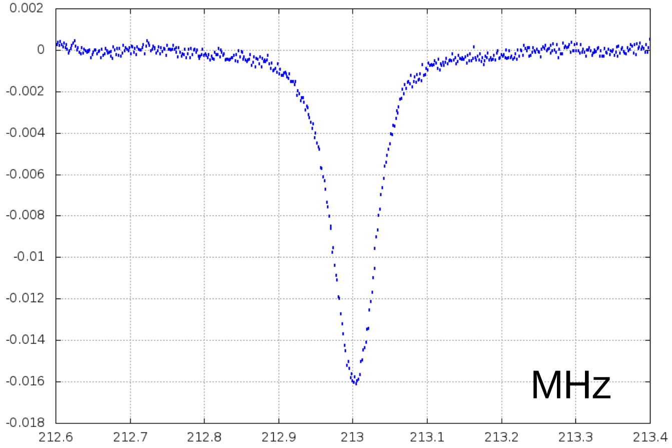

Rotation (coil touching)
0.05
0
-0.05
-0.1
-0.15
-0.2
-0.25
-0.3
212.6
212.7
212.8
212.9
213
213.1
213.2
213.3
213.4
MHz

NMR Thermal Equilibrium

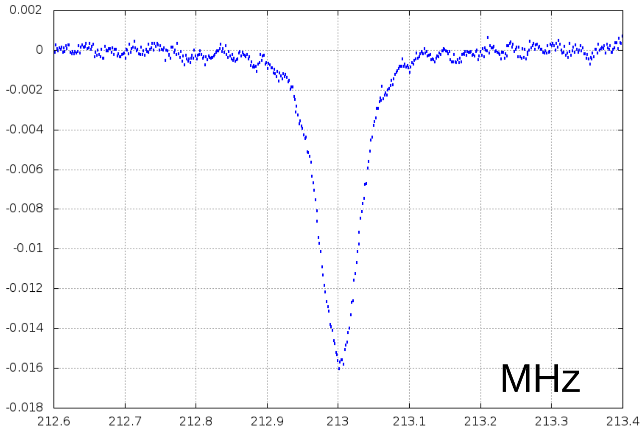
Standard



Rotation (coil not touching)



Rotation (coil touching)



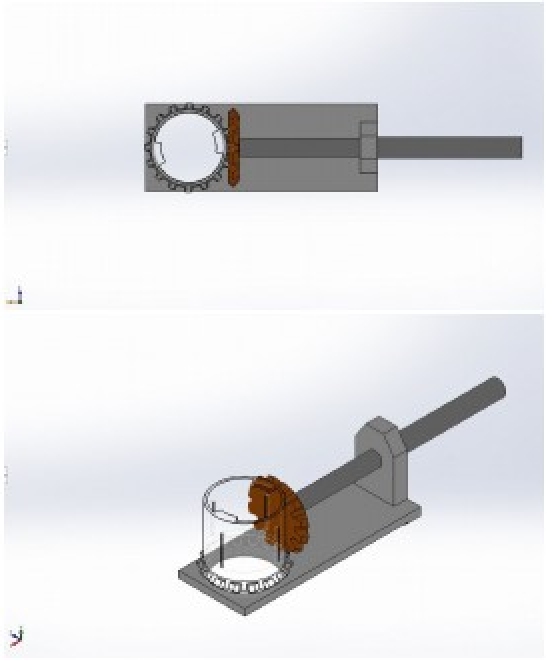
Average Area: -0.093471 (0.133%)
Average Temp: 1.706 K (0.023%)
TE Polarization: 0.301%
Calibration Constant: -3.204 (0.135%)

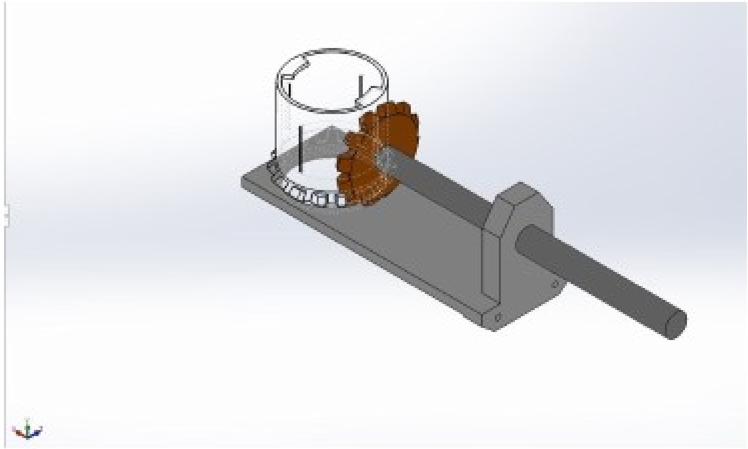
Average Area: -0.086741 (0.167%)
Average Temp: 1.742 K (0.15%)
TE Polarization: 0.293%
Calibration Constant: -3.382 (0.255%)

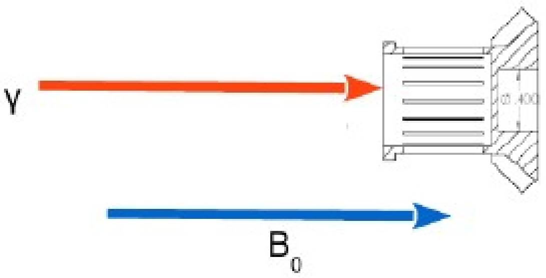
Average Area: -0.08982 (0.277%)
Average Temp: 1.739 K (0.335%)
TE Polarization: 0.294%
Calibration Constant: -3.389 (0.523%)

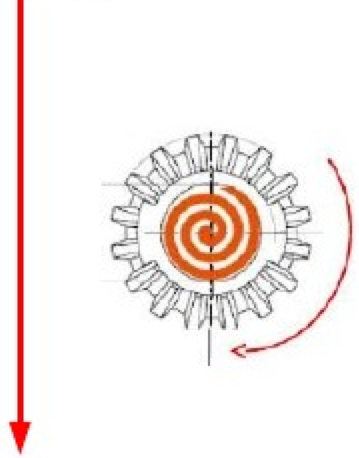
A Likely WACS Version

Rotation Design







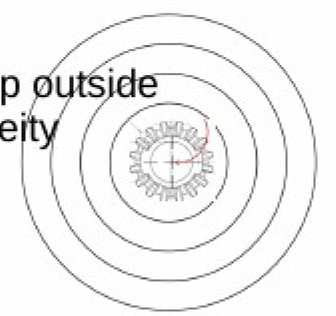


Vertical and Rotational

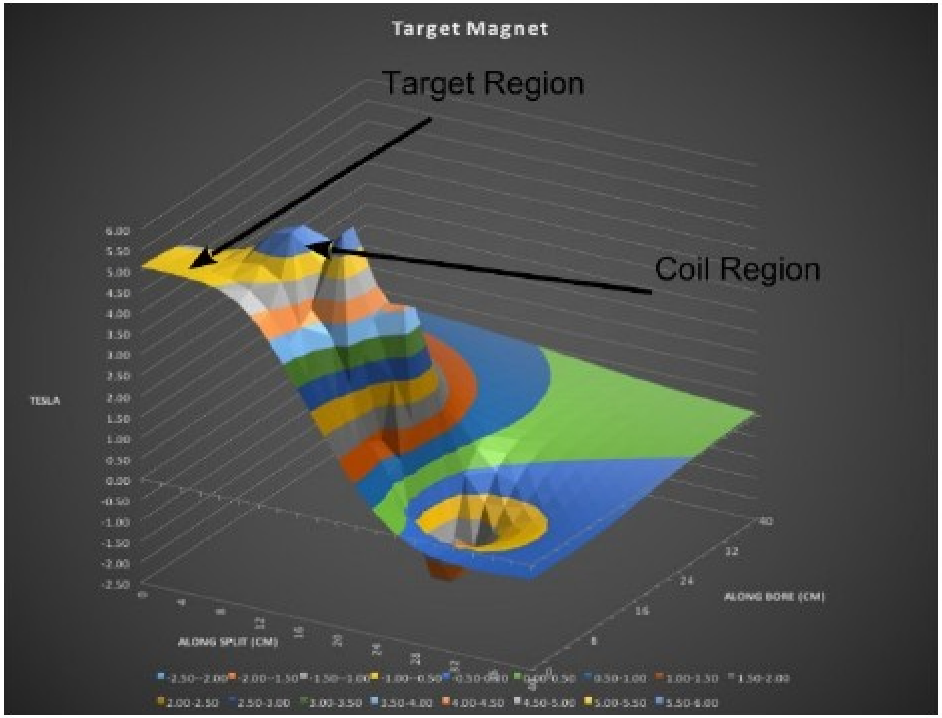
- Control target position
- Rotate while moving up and down
- Similar to standard dimensions 3 cm x 2.7 cm
- Also possible to expand dimensions
- Keep rotation cycles consistent per physics run for systematic regularity

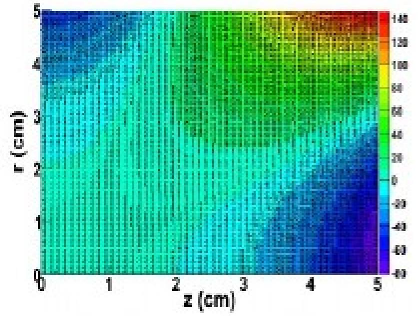
Field Constraints

- Rotation rate $\omega_f > f_0 (B_r) t_1$
- Field region would allow larger cups up to 5 cm diameter
- Size of cup ultimately limited by fridge
- Position NMR loop on the side of the field

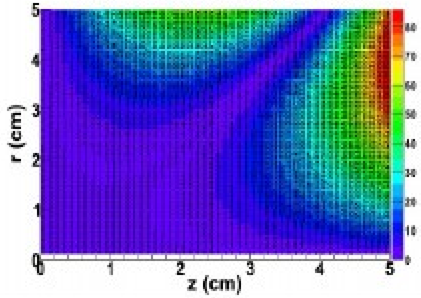


Expand size of cup outside of homogeneity





Bz-Homogeneity



Br-Homogeneity

THANK YOU

The Trouble with ND3

- Needs warm (87 K) and cold (1-4 K) to get maximum polarization
- There is a need for the cold produced centers which are not known or understood
- It doesn't stay optimized after cold irradiation
- Never been produced outside of experiments so not clear what temperature, dose or beam energy is needed, or how best to anneal for optimization
- So far only one data point :

  ($1X10^{15}$ e^{-}/cm^{2} ,14MeV, 4K)~18%

  d-but is use under the assumption that the lineshape behaves the same as ND3 and the max polarization from irradiation is about the same